Evaluation of exclusive $N\pi$ structure functions

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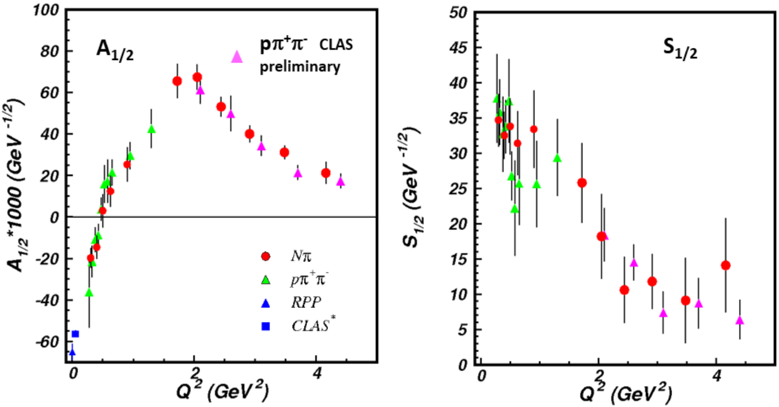
Nucleon Resonance Electrocouplings from Data On Exclusive Meson Electroproduction with CLAS

Exclusive meson electroproduction channels	Excited proton states	Q^2-ranges for extracted $\gamma_v pN^*$ electrocouplings, GeV^2
$\pi^0 p$, $\pi^+ n$	$\Delta(1232)3/2^+$ $N(1440)1/2^+$,$N(1520)3/2^-$, $N(1535)1/2^-$	0.16-6.0 0.30-4.16
$\pi^+ n$	$N(1675)5/2^-$, $N(1680)5/2^+$ $N(1710)1/2^+$	1.6-4.5
ηp	$N(1535)1/2^-$	0.2-2.9
$\pi^+\pi^- p$	$N(1440)1/2^+$, $N(1520)3/2^-$ $\Delta(1620)1/2^-$, $N(1650)1/2^-$, $N(1680)5/2^+$, $\Delta(1700)3/2^-$, $N(1720)3/2^+$, $N'(1720)3/2^+$	0.25-1.50 2.0-5.0 (preliminary) 0.5-1.5

The website with numerical results and references:
https://userweb.jlab.org/~mokeev/resonance_electrocouplings/

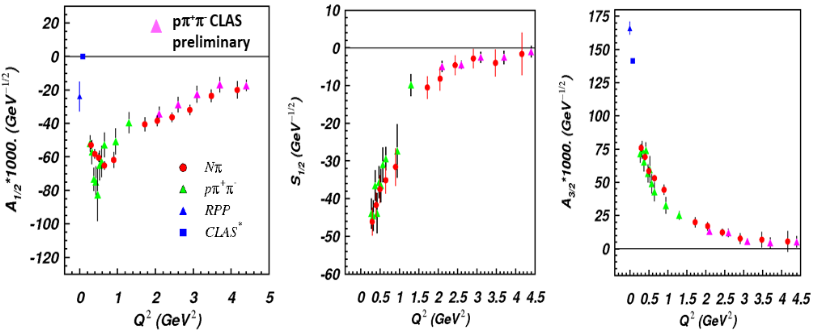
Interpolation at 0.5 GeV^2<Q^2<7.0 GeV^2 for resonances in the mass range of W<1.8 GeV
is available in: A.N. Hiller Blin et al., Phys. Rev. C 100, 035201 (2019)

Electrocouplings of N(1440)1/2$^+$ from πN and $\pi^+\pi^-$p Electroproduction off Proton Data



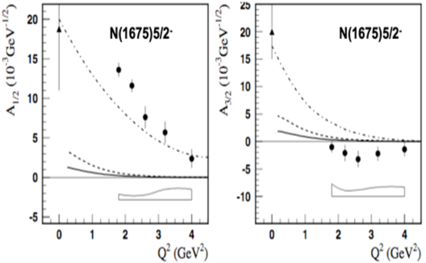
Consistent results on N(1440)1/2$^+$ electrocouplings from independent studies of two major πN and $\pi^+\pi^-$p electroproduction channels with different non-resonant contributions allow us to evaluate the systematic uncertainties of these quantities in a nearly model-independent way

Electrocouplings of N(1520)3/2$^-$ from πN and $\pi^+\pi^-$p Electroproduction off Proton Data



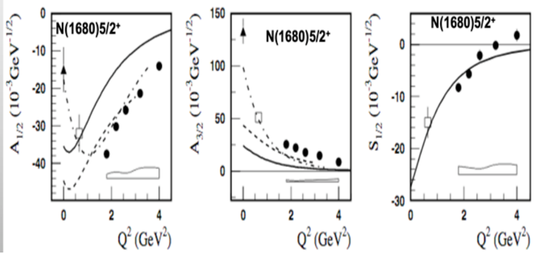
Consistent results from πN and $\pi^+\pi^-$p electroproduction off proton data on electrocouplings of N(1440)1/2$^+$ and N(1520)3/2$^-$ resonances with the biggest combined contribution into the resonant parts of both channels at W<1.55 GeV strongly support the capabilities of the developed reaction models for credible extraction of resonance electrocouplings from independent analyses of both πN and $\pi^+\pi^-$p electroproduction

Electrocouplings of High-Lying Resonances from π^+n Electroproduction off Proton Data



K.Park et al., CLAS Collab.,
Phys. Rev. C91, 045203 (2015).

The first results on electrocouplings of $N(1675)5/2^-$, $N(1680)5/2^+$, and $N(1710)1/2^+$ resonances have Become available at $2.0<Q2<5.0$ GeV^2 from the CLAS $n\pi^+$ electroproduction data



Summary of Published CLAS Data on Exclusive Meson Electroproduction off Protons in the N* Excitation Region

Hadronic final state	Covered W-range, GeV	Covered Q^2-range, GeV^2	Measured observables
$\pi^+ n$	**1.1-1.38** **1.1-1.55** **1.1-1.7** **1.6-2.0**	**0.16-0.36** **0.3-0.6** **1.7-4.5** **1.8-4.5**	$d\sigma/d\Omega$ $d\sigma/d\Omega$ $d\sigma/d\Omega$, A_b $d\sigma/d\Omega$
$\pi^0 p$	**1.1-1.38** **1.1-1.68** **1.1-1.39**	**0.16-0.36** **0.4-1.8** **3.0-6.0**	$d\sigma/d\Omega$ $d\sigma/d\Omega$, A_b,A_t,A_{bt} $d\sigma/d\Omega$
ηp	**1.5-2.3**	**0.2-3.1**	$d\sigma/d\Omega$
$K^+\Lambda$	**thresh-2.6**	**1.40-3.90** **0.70-5.40**	$d\sigma/d\Omega$ P^0, P'
$K^+\Sigma^0$	**thresh-2.6**	**1.40-3.90** **0.70-5.40**	$d\sigma/d\Omega$ P'
$\pi^+\pi^- p$	**1.3-1.6** **1.4-2.1** **1.4-2.0**	**0.2-0.6** **0.5-1.5** **2.0-5.0**	**Nine 1-fold differential cross sections**

- $d\sigma/d\Omega$–CM angular distributions
- A_b,A_t,A_{bt}-longitudinal beam, target, and beam-target asymmetries
- P^0, P' –recoil and transferred polarization of strange baryon

Over 150,000 data points!

Almost full coverage of the final state hadron phase space

The measured observables from CLAS are stored in the
CLAS Physics Database http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi

Objective

Evaluation of exclusive $N\pi$ differential cross sections in an arbitrary point of the resonance region at Q^2 <5 GeV^2, W <1.7 GeV and for any beam energy.

- The first step: the evaluation of the $N\pi$ exclusive structure functions

$$\frac{d\sigma_u}{d\Omega}(W,Q^2,\cos\vartheta), \quad \frac{d\sigma_t}{d\Omega}(W,Q^2,\cos\vartheta), \quad \frac{d\sigma_l}{d\Omega}(W,Q^2,\cos\vartheta),$$
$$\frac{d\sigma_{tt}}{d\Omega}(W,Q^2,\cos\vartheta),$$
$$\frac{d\sigma_{lt}}{d\Omega}(W,Q^2,\cos\vartheta).$$

for electroproduction channels $\gamma^* p \rightarrow \pi^+ n$, $\gamma^* p \rightarrow \pi^0 p$ at $W <$ 1.7 GeV, $Q^2 <$ 5 GeV^2

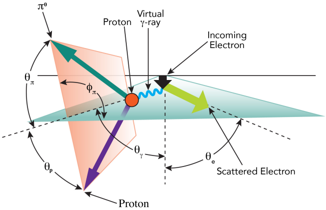
Cross sections and structure functions

The structure functions can be obtained by fitting the CLAS experimental data:

$$\frac{d\sigma}{d\Omega}(W,Q^2,\cos\vartheta,\varphi) = \frac{d\sigma_u}{d\Omega}(W,Q^2,\cos\vartheta) \; + \; \varepsilon \cdot \frac{d\sigma_{tt}}{d\Omega}(W,Q^2,\cos\vartheta)\cdot\cos 2\varphi \; +$$

$$+ \sqrt{2\varepsilon(1+\varepsilon)}\cdot\frac{d\sigma_{lt}}{d\Omega}(W,Q^2,\cos\vartheta)\cdot\cos\varphi$$

where $\frac{d\sigma_u}{d\Omega}$, $\frac{d\sigma_{tt}}{d\Omega}$, $\frac{d\sigma_{lt}}{d\Omega}$ stand for: unpolarized, transverse-transverse, and longitudinal-transverse structure functions respectively; ε - polarization of a virtual photon.

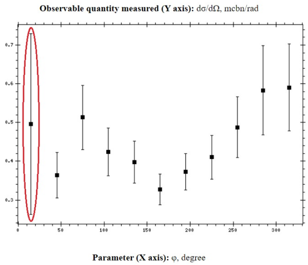


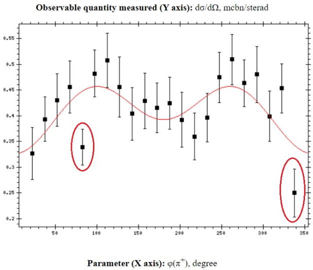
The studied reactions:

$\gamma^* p \to \pi^+ n$

$\gamma^* p \to \pi^0 p$

Data selection





- The data points with relative uncertainties > 0.7 were excluded.
- The data points which deviated from fit $>\pm 1.5\ \sigma$ were excluded.
- $(W, Q^2, \cos\vartheta)$ bins with less than 4 data points were excluded.

The methods for extraction of the exclusive structure functions

- Method 0. The data cover the full φ range $[0, 2\pi]$. The data fit according to equation:

$$\frac{d\sigma}{d\Omega}(W,Q^2,\cos\vartheta,\varphi) = \frac{d\sigma_u}{d\Omega}(W,Q^2,\cos\vartheta)+\varepsilon\cdot\frac{d\sigma_{tt}}{d\Omega}(W,Q^2,\cos\vartheta)\cdot\cos 2\varphi+\sqrt{2\varepsilon(1+\varepsilon)}\cdot\frac{d\sigma_{lt}}{d\Omega}(W,Q^2,\cos\vartheta)\cdot\cos\varphi$$

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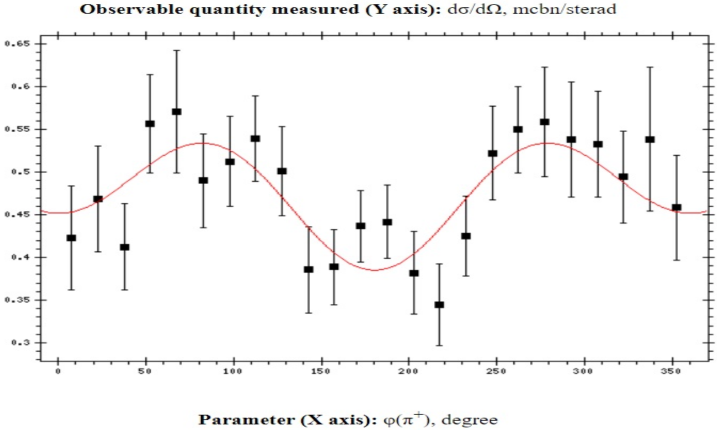
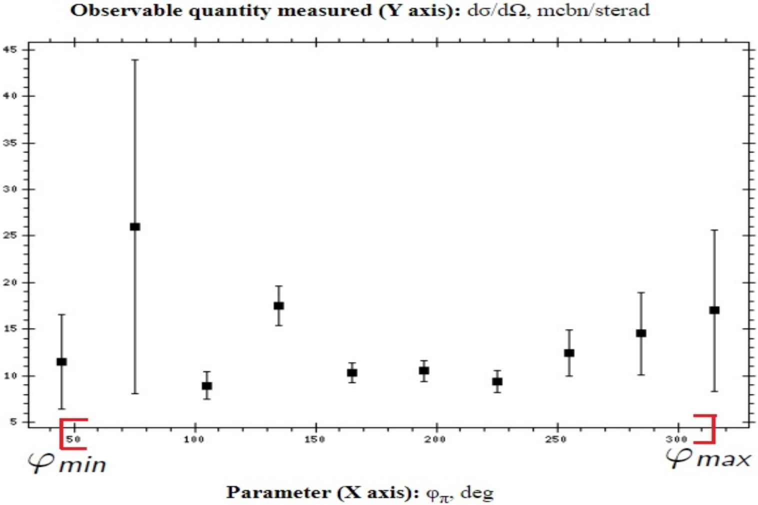


The methods for extraction of exclusive structure functions



The methods for extraction of exclusive structure functions

- Method 1: The data are available in $\Delta\varphi$ range $[\varphi_{min},\varphi_{max}]$

$$\frac{d\sigma_u}{d\Omega}_{method\ 1} = \frac{1}{\phi_{max} - \phi_{min}} \left[\int\limits_{\varphi_{min}}^{\varphi_{max}} \frac{d\sigma}{d\Omega}_{exp} d\varphi - \varepsilon \cdot \frac{d\sigma_{tt}}{d\Omega} \int\limits_{\varphi_{min}}^{\varphi_{max}} \cos 2\varphi d\varphi - \sqrt{2\varepsilon(1+\varepsilon)} \cdot \frac{d\sigma_{lt}}{d\Omega} \int\limits_{\varphi_{min}}^{\varphi_{max}} \cos\varphi d\varphi \right]$$

$\frac{d\sigma}{d\Omega}_{exp}$ stands for the experimental data.

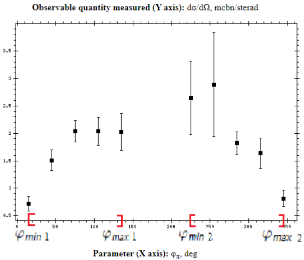
$\frac{d\sigma_{tt}}{d\Omega}$, $\frac{d\sigma_{lt}}{d\Omega}$ are determined from the data fit from φ_{min} to φ_{max}

- Method 2:

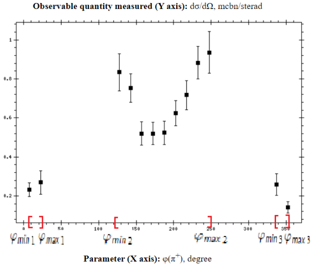
$$\frac{d\sigma_u}{d\Omega}_{method\ 2} = \frac{1}{2\pi} \left[\int\limits_{\varphi_{min}}^{\varphi_{max}} \frac{d\sigma}{d\Omega}_{exp} d\varphi + \int\limits_{0}^{\varphi_{min}} \frac{d\sigma}{d\Omega}_{proj} d\varphi + \int\limits_{\varphi_{max}}^{2\pi} \frac{d\sigma}{d\Omega}_{proj} d\varphi \right]$$

$\frac{d\sigma}{d\Omega}_{proj}$ is determined from the data fit from φ_{min} to φ_{max}

The methods for extraction of the exclusive structure functions



One gap



Two gaps

- Methods 3 and 4: There are one (method 3) or two (method 4) gaps in the φ-dependence of the experimental data

$$\frac{d\sigma_u}{d\Omega}_{method\,3,\,4} = \frac{\sum_i \left[\int_{\varphi_{min\,i}}^{\varphi_{max\,i}} \frac{d\sigma}{d\Omega}_{exp} d\varphi \right]}{\sum_i \left[(\varphi_{maxi} - \varphi_{mini}) + r_{tt} \cdot \left(\int_{\varphi_{min\,i}}^{\varphi_{max\,i}} \cos 2\varphi d\varphi \right) + r_{lt} \cdot \left(\int_{\varphi_{min\,i}}^{\varphi_{max\,i}} \cos \varphi d\varphi \right) \right]}$$

where $r_{tt} = \varepsilon \cdot \frac{d\sigma_{tt}}{d\Omega} / \frac{d\sigma_u}{d\Omega}$, $r_{lt} = \sqrt{2\varepsilon(1+\varepsilon)} \cdot \frac{d\sigma_{lt}}{d\Omega} / \frac{d\sigma_u}{d\Omega}$

The methods for extraction of the exclusive structure functions

$\frac{d\sigma_{tt}}{d\Omega}$, $\frac{d\sigma_{lt}}{d\Omega}$ via Method i (i = 1,2,3,4):

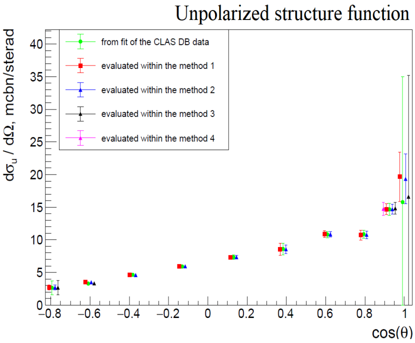
$$\frac{d\sigma_{tt}}{d\Omega}_{method\ i} = \frac{1}{\varepsilon} \cdot \frac{d\sigma_{u}}{d\Omega}_{method\ i} \cdot r_{tt}$$

$$\frac{d\sigma_{lt}}{d\Omega}_{method\ i} = \frac{1}{\sqrt{2\varepsilon(1+\varepsilon)}} \cdot \frac{d\sigma_{u}}{d\Omega}_{method\ i} \cdot r_{lt}$$

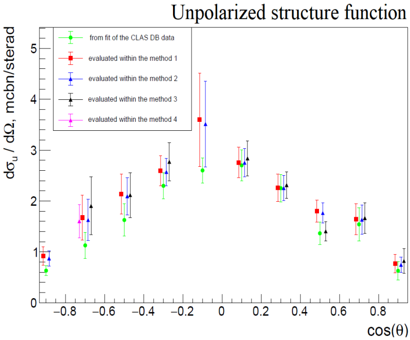
$$r_{tt} = \varepsilon \cdot \frac{d\sigma_{tt}}{d\Omega} \Big/ \frac{d\sigma_{u}}{d\Omega}$$

$$r_{lt} = \sqrt{2\varepsilon(1+\varepsilon)} \cdot \frac{d\sigma_{lt}}{d\Omega} \Big/ \frac{d\sigma_{u}}{d\Omega}$$

Unpolarized structure functions from different methods



a)



b)

a) $\pi^+ n,\ W = 1.31\ GeV,\ Q^2 = 0.3\ GeV^2$
b) $\pi^0 p,\ W = 1.4\ GeV,\ Q^2 = 0.65\ GeV^2$

Separation between transverse and longitudinal structure functions

The transverse $\frac{d\sigma_t}{d\Omega}$ and longitudital $\frac{d\sigma_l}{d\Omega}$ structure functions were obtained from unpolorized $\frac{d\sigma_u}{d\Omega}$ structure function by employing the experimental results on the ratio $R = \frac{d\sigma_l}{d\Omega} / \frac{d\sigma_t}{d\Omega}$

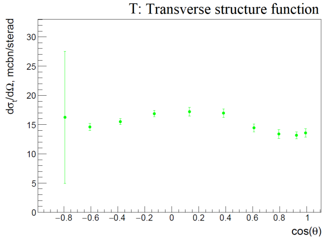
$$\frac{d\sigma_u}{d\Omega} = \frac{d\sigma_t}{d\Omega} + \varepsilon \frac{d\sigma_l}{d\Omega}, \qquad \varepsilon = \left(1 + 2\frac{\nu^2 + Q^2}{Q^2} \tan^2 \frac{\theta}{2}\right)^{-1}$$

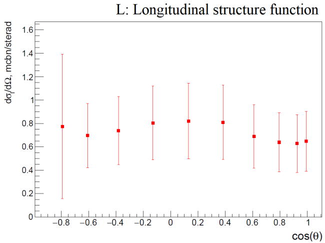
$$\nu = E_{beam} - E^{'} = \frac{W^2 + Q^2 - M_p^2}{2M_p} \qquad \sin^2 \frac{\theta}{2} = \frac{Q^2}{4E_{beam}(E_{beam} - \nu)}$$

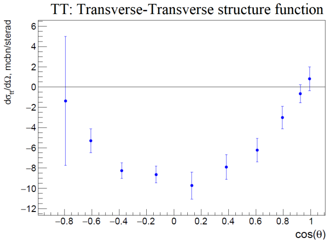
ε is polarisation of a virtual photon
$E^{'}, \theta$ are the energy and the angle of scattered electron in lab frame.

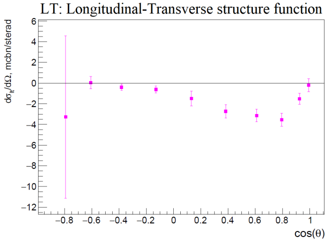
$$\frac{d\sigma_t}{d\Omega} = \frac{\frac{d\sigma_u}{d\Omega}}{1 + \varepsilon R} \qquad \frac{d\sigma_l}{d\Omega} = \frac{R\frac{d\sigma_u}{d\Omega}}{1 + \varepsilon R}$$

The structure functions for $\pi^{+}n$ exclusive channel at $W = 1.21\ GeV$, $Q^2 = 0.3\ GeV^2$

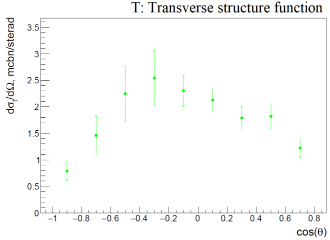


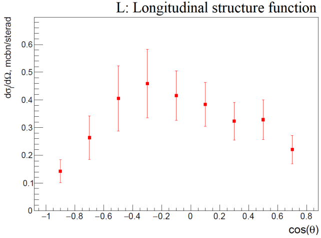


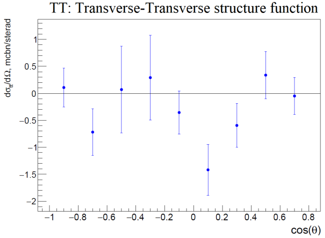


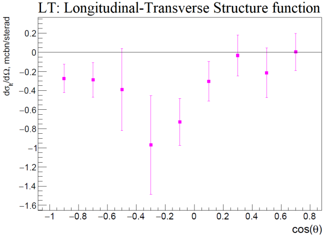


The structure functions for $\pi^0 p$ exclusive channel at $W = 1.46\ GeV,\ Q^2 = 0.65\ GeV^2$









The developed website

https://clas.sinp.msu.ru/~almaz/

Measurmnet : gvp--->π^0p, Wmin=1.22 GeV, Wmax=1.22 GeV, Q^2min=1.3 GeV^2, Q^2max=1.6 GeV^2, ε = 0.689

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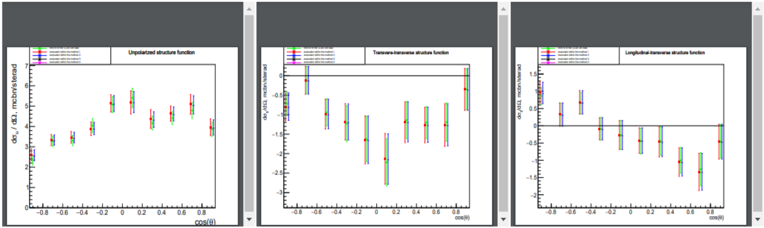

Different data sets are shifted for visibility

Calculation Method Information

$cos(theta)$	$\frac{d\sigma_U}{d\Omega}$ (fit)	$\Delta\frac{d\sigma_U}{d\Omega}$ (fit)	$\frac{d\sigma_U}{d\Omega}$ (method 1)	$\Delta\frac{d\sigma_U}{d\Omega}$ (method 1)	$\frac{d\sigma_U}{d\Omega}$ (method 2)	$\Delta\frac{d\sigma_U}{d\Omega}$ (method 2)
-0.9	2.33744	0.223566	2.60608	0.292231	2.58369	0.268526
-0.7	3.26864	0.253901	3.33606	0.272976	3.33044	0.251121
-0.5	3.30659	0.249835	3.46804	0.2806	3.45459	0.258058
-0.3	4.0469	0.339893	3.88748	0.330068	3.90076	0.303885
-0.1	5.07419	0.388251	5.13293	0.422521	5.12803	0.38866
0.1	5.40086	0.472111	5.18295	0.564135	5.20111	0.518618
0.3	4.16526	0.339022	4.37124	0.458865	4.33691	0.386539
0.5	4.41164	0.321278	4.63586	0.373669	4.61717	0.343575
0.7	4.78285	0.388726	5.08721	0.487133	5.06185	0.447712
0.9	3.8546	0.348915	3.96093	0.404399	3.95207	0.371838

$cos(theta)$	$\frac{d\sigma_{tt}}{d\Omega}$ (fit)	$\Delta\frac{d\sigma_{tt}}{d\Omega}$ (fit)	$\frac{d\sigma_{tt}}{d\Omega}$ (method 1)	$\Delta\frac{d\sigma_{tt}}{d\Omega}$ (method 1)	$\frac{d\sigma_{tt}}{d\Omega}$ (method 2)	$\Delta\frac{d\sigma_{tt}}{d\Omega}$ (method 2)
-0.9	-0.717425	0.304546	-0.799878	0.35943	-0.793006	0.354775
-0.7	-0.113826	0.349543	-0.116174	0.356993	-0.115978	0.356373
-0.5	-0.93919	0.349614	-0.985048	0.382556	-0.981227	0.37985
-0.3	-1.23006	0.461747	-1.1816	0.465464	-1.18564	0.465336
-0.1	-1.62746	0.579204	-1.6463	0.614428	-1.64473	0.611564
0.1	-2.22263	0.602596	-2.13295	0.650441	-2.14043	0.646001
0.3	-1.13804	0.474256	-1.19432	0.522381	-1.18494	0.514095
0.5	-1.20363	0.413173	-1.2648	0.455394	-1.2597	0.451875
0.7	-1.18991	0.492034	-1.26563	0.546954	-1.25932	0.542262
0.9	-0.341707	0.520884	-0.351133	0.537393	-0.350348	0.536011

$cos(theta)$	$\frac{d\sigma_{lt}}{d\Omega}$ (fit)	$\Delta\frac{d\sigma_{lt}}{d\Omega}$ (fit)	$\frac{d\sigma_{lt}}{d\Omega}$ (method 1)	$\Delta\frac{d\sigma_{lt}}{d\Omega}$ (method 1)	$\frac{d\sigma_{lt}}{d\Omega}$ (method 2)	$\Delta\frac{d\sigma_{lt}}{d\Omega}$ (method 2)
-0.9	0.861661	0.253605	0.960691	0.316222	0.952437	0.310931
-0.7	0.318997	0.328971	0.325577	0.33776	0.325028	0.337033
-0.5	0.65271	0.315251	0.68458	0.339218	0.681925	0.337237
-0.3	-0.0890713	0.331811	-0.0855625	0.318904	-0.0858548	0.31998
-0.1	-0.266652	0.414909	-0.269739	0.420805	-0.269481	0.420315
0.1	-0.445159	0.377489	-0.427198	0.367134	-0.428695	0.367945
0.3	-0.445811	0.409871	-0.467857	0.434606	-0.464183	0.430424
0.5	-1.00254	0.376058	-1.05349	0.411408	-1.04925	0.408458
0.7	-1.25881	0.480447	-1.33892	0.537979	-1.33224	0.533061
0.9	-0.448605	0.489387	-0.46098	0.506805	-0.459949	0.505343

Conclusions and outlook

- Exclusive structure functions $\frac{d\sigma_u}{d\Omega}$, $\frac{d\sigma_t}{d\Omega}$, $\frac{d\sigma_l}{d\Omega}$, $\frac{d\sigma_{tt}}{d\Omega}$, $\frac{d\sigma_{lt}}{d\Omega}$ have become available from the CLAS $\pi^+ n$, $\pi^0 p$ electroproduction channels of experimental data at $W \in [1.1, 1.7]$ GeV, $Q^2 \in [0.25, 5]$ GeV^2 for the first time.

- Evaluation of two-fold differential $\pi^+ n$, $\pi^0 p$ virtual photon cross sections in an arbitrary point of the aforementioned kinematic area is in progress.

- The developed methods can be used for extraction of $N\pi$ exclusive srtucture functions in the DIS region.